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Hydrogen lines in LAMOST low-resolution spectra of RR Lyrae stars ☆

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HIGHLIGHTS

- We select single epoch spectra of RR Lyrae stars from LAMOST pilot survey.
- We use cross-correlation method to study the differential radial velocities.
- We capture three RR Lyrae stars in fast expansion phase with hypersonic shock wave features in the spectra.

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ABSTRACT

The LAMOST pilot survey has produced a data release containing over 600,000 stellar spectra. By cross-checking with a large time series photometric database of RR Lyrae stars in high Galactic latitude regions, we found a total number of 157 RR Lyrae stars that have been observed with LAMOST. In this sample, we successfully captured three RR Lyrae stars in the fast expansion phase, all of them showing hypersonic shock wave features in the Balmer line region. We fit the shape of Hα line region and determine that the emission feature seen within the broadened Hα absorption line suggests hypersonic relative motion in the atmospheres of these three objects. With a further LAMOST survey of millions of stars, we plan to capture a large sample of RR Lyrae stars in their hypersonic expansion phase, and therefore provide a large database for the study of the internal structure and the pulsation mechanism of RR Lyrae stars.

1. Introduction

RR Lyrae stars show variabilities in observational quantities including radial velocity, luminosity and color due to their pulsations. The RR Lyrae pulsation features a slow contraction after a fast expansion, which can be detected using radial velocity line shifts. Although generally showing regularity in their pulsation, RR Lyrae stars have very complicated atmospheric hydrodynamic processes that have been revealed by high resolution spectroscopy of a few bright RR Lyrae stars (e.g., Chadid et al., 2008; Chadid, 2011). Evidence that hypersonic shock wave, a shock wave where radiative phenomena have major a impact, exists in the RR Lyrae stars has been reported by Chadid et al. (2008). Hereafter, in this paper we define the hypersonic shock phase as the phase when the hypersonic shock wave takes place. Observations indicate that the strong shocks propagate for about 4% of the period in a pulsation cycle, based on the evidence of shock signatures such as line doublings and emission in hydrogen lines (Preston and Paczynski, 1964; Preston et al., 1965). For large amplitude RR Lyraes, motions in the atmosphere can become hypersonic. During a pulsation cycle, minor emission caused by the shock of ballistically falling outer material onto the bottom of the atmosphere during the bump phase (at phase ~ 0.7) can be observed in high resolution spectra (Preston, 2011).

Spectral signatures in the fast expansion phase include emission features in the Balmer lines (Preston, 2011), the appearance of helium lines, and the disappearance of neutral metallic lines (Chadid and Gillet, 1996; Chadid et al., 2008). In the Balmer lines, a prominent narrow emission line is coupled with a broad, red

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shifted absorption feature. The emission line is explained by a radiation-dominated shock wave propagating in the outer photosphere (Chadid et al., 2008). Meanwhile, the intensity of the absorption lines becomes weaker as the shock wave pushes outwards, and then becomes strong again when the shock wave is no longer radiation-dominated.

In order to better understand the physics of RR Lyrae pulsations, spectroscopy of a large sample is needed. Unfortunately, the duration of the hypersonic shock phase is typically around 30 min, much shorter than most of the exposure times required by high resolution spectroscopic observations, hence only very few cases have been observationally captured so far (Preston, 2011; Preston, 2009; Chadid et al., 2008).

Highly-multiplexed, large sky area surveys such as LEGUE (LAMOST Experiment on Galactic Understanding and Exploration; Deng et al., 2012) offer opportunities to observe a large sample of RR Lyrae stars with medium-low resolution spectroscopy. In this paper we present discoveries of this rare phenomenon by the pilot mission of LEGUE, and discuss another viable way to capture the hypersonic expansion phase in RR Lyrae stars using low resolution multi-epoch spectroscopy.

2. Data and observations

The Catalina Survey Data Release 1 (DR1) of time series photometric data has recently been published, including a catalogue containing 12397 type-ab RR Lyraes (RR ab) identified from fitting of the light curves. It covers about 20,000 deg^2 of sky area with $0^\circ < \alpha < 360^\circ$ and $-22^\circ < \delta < 65^\circ$ (Drake et al., 2013). In this catalogue, the RR Lyrae stars are essentially uniformly distributed, and the upper limit of their heliocentric distances is about 60 kpc (Drake et al., 2013). The visual magnitude limit of the catalogue goes from 11 to 20 Mag in *V* band.

The footprint of the LEGUE survey (Deng et al., 2012; see also Chen et al., 2012;Yang et al., 2012; Zhang et al., 2012) largely overlaps with the Catalina catalogue. Thus, it gives us an opportunity to study RR Lyraes with LEGUE spectra. The system carrying out the LAMOST survey has 4000 fibers in the focal plane, corresponding to a roughly 20 deg^2 field of view (see Cui et al., 2012 for more details). The resolution of LEGUE spectra is about $R \approx 1800$ with a spectral wavelength coverage of 3700< λ < 9100Å (Zhao et al., 2012). By the end of the survey, nearly 10 million spectra of stars in the Galaxy will be collected. This huge number of spectra should be of great help to better understand the nature of our Galaxy, such as the Galactic merger history and disk substructure and evolution. A pilot survey aimed at testing the system performance was conducted from Oct 2011 to Jun 2012. Each set of targets (a plate) is a combination of 2–3 separate exposures. The duration of each single exposure varies from 600 to 1800 s, which is approximately the typical duration of the RR Lyrae hypersonic shock phase. This cadence plus the sheer number of spectra that LAMOST will observe makes it promising for studying the physics of hypersonic shocks in RR Lyrae stars.

More than 600,000 stellar spectra have been released from the LAMOST pilot survey (Luo et al., 2012). Cross-matching the Catalina catalogue with the LEGUE pilot survey data found 157 RRab stars which have been spectroscopically observed by LAMOST. In standard data processing, object spectra are extracted by a 2D pipeline, then combined after wavelength calibration and sky subtraction (Zhao et al., 2012; Guo et al., 2012). Therefore the regular data release does not contain information from single exposures. Because RR Lyraes pulsate over short time scales (roughly a few hours), we can use the individual spectra from repeated exposures of the same plate to explore changes in the properties of these stars on ~30-minute time scales. Instead of combining the single spectra of all exposures of a plate and running regular 1D pipeline tasks, we directly extract the single spectra of all RR Lyrae targets from the 2D pipeline process. These single spectra have already passed flat fielding, wavelength calibration and sky subtraction, and are ready for the analysis described below. In the end, a total number of 397 single-epoch spectra of those 157 stars were collected. Each star has two or three exposures at different epochs, corresponding to two or three spectra.

3. Analysis and results

LEGUE covers the whole optical wavelength range using a blue arm (3700–6000 Å) and a red arm (5700–9100 Å). The system performance is typically better in the red arm in terms of throughput and wavelength calibration. To ensure clarity and uniform velocity measurements, we use only the Hα line in the red arm as the radial velocity indicator, and only locally normalise the spectra in the range of 6450< λ <6750 Å. The quantity σ for each of the spectra is then calculated from the RMS of the two fractions of the spectra at 6450< λ <6500 Å and 6700< λ <6750 Å, within which the spectra are continuum dominated. The signal to noise ratio (S/N) is obtained by $S/N = 1/\sigma$. We select objects with $S/N > 15$ for the following analysis, leaving a sample of 211 spectra belonging to 99 individual stars.

3.1. Search for stars observed during the fast expansion phase

For the purpose of the current work, it is not necessary to measure the radial velocity from each single spectrum. The differential velocity between two epochs is sufficient for the phase determination of the RR Lyrae stars. Hence, we apply a cross-correlation method to estimate the differential radial velocity, Δ(RV), of each pair of spectra for a given star. To satisfy this requirement, each star must have more than one spectrum among those 211 high S/N spectra, which gives us a final sample of 184 spectra from 72 stars. Among those stars, 40 stars have three spectra and 32 stars have two spectra. Finally, we have 152 pairs of spectra with corresponding differential radial velocities from 72 stars in total.

In order to obtain the velocity shift for each pair of spectra, the first observed spectrum in a pair is treated as a template and the second one is shifted by 1 km s^{-1} steps over a range of -250 km s^{-1} to 250 km s^{-1}. The cross-correlation index of the two spectra at each step is calculated from the normalised spectra within 6510< λ <6610 Å, in which the Hα line is located. The Δ(RV) is determined as the velocity shift at which the index peaks. This is regarded as the most likely Δ(RV) of the pair.

Although the Catalina catalogue provides several observable quantities for the RR Lyrae stars, including the pulsation period and amplitude, the ephemeris given in the catalogue is not reliable now because the observations were taken more than 7 years ago. Despite this, we can still simulate the distribution of differential radial velocity for LEGUE observations for a given period and normalised amplitude. For each of the 72 stars in our sample, we first randomly select a zero point phase between 0 and 1 for the initial exposure. Then, the simulated phase of the second and third (if it exists) exposure is determined from the temporal spacing of the observations and the known pulsation period from the Catalina catalogue. The $V-$band light curve amplitude of each star's variability (in magnitudes) from the Catalina catalogue is converted to a radial velocity amplitude using the relations for these quantities from Sesar (2012). Then the phase-RV$_{norm}$ relation given by Sesar (2012) is used to derive the radial velocity of each simulated exposure. The phase-RV$_{norm}$ relation for the Balmer lines given by Sesar (2012) is not valid for phase > 0.95, and therefore a linear interpolation is adopted for this region. The observations for each